Met Office

# A particle size dependent wet deposition scheme for NAME

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**Abstract**

Wet scavenging of atmospheric aerosols has long since been known to depend on the particle size. Here we describe a new particle size dependent wet deposition scheme for the Lagrangian atmospheric dispersion model NAME. The scheme, and its origins, are documented, details for the user on invoking the particle size dependent wet scavenging scheme are given and comparisons are made between the new scheme and the original bulk wet scavenging scheme for some typical aerosol species.

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# 1 Introduction

Wet deposition is the removal of material from the atmosphere by precipitation elements. In regions of precipitation, wet deposition processes are highly efficient in scavenging atmospheric aerosols. Aerosols can enter precipitation elements in different ways. Within cloud they can act as cloud condensation (or ice) nuclei in the formation of cloud droplets (or cloud ice crystals). Aerosols can also enter cloud droplets (or cloud ice crystals) by impaction processes. A fraction of these cloud droplets (or cloud ice crystals) will grow into precipitation elements, thereby removing the aerosols contained within the precipitation elements from the atmosphere. This in-cloud wet scavenging process is commonly referred to as rainout. Below cloud, aerosols can be swept out by impaction with falling precipitation elements. This below-cloud scavenging process is commonly referred to as washout.

The efficiency of below-cloud and in-cloud scavenging processes is known to depend on the aerosol size, the aerosol properties, the cloud phase (within cloud) or the precipitation type (below cloud) and the precipitation rate. Good cloud condensation nuclei are submicron in size ($\sim$0.08 - 1.0 $\mu$m) and hygroscopic (water absorbing). Below-cloud scavenging is efficient for very small particles (< $\sim$0.01 $\mu$m), due to their Brownian motion, and for coarse particles (of the order of a few microns), which are readily collected by interception (due to the particle's size) and by impaction (due to the particle's inertia). Below-cloud scavenging is much less efficient for aerosols in the intermediate size range, which tend to be swept along the streamlines around falling precipitation elements, thereby escaping capture. This minimum region in the collection efficiency for particle sizes of $\sim$0.1 - 1.0 $\mu$m is known as the Greenfield gap [6].

Traditionally, atmospheric dispersion models use bulk wet scavenging parametrizations, where the change in mass, $M$, (e.g., of a Lagrangian particle or an Eulerian grid box) due to wet deposition is modelled by a simple loss equation using the concept of a constant scavenging coefficient ($\Lambda$),

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\Lambda M. \tag{1}$$

For aerosols, the scavenging coefficient represents the mean scavenging rate over all particle sizes. NAME has had a bulk wet deposition scheme since the early days of its development and, over the years, the scheme has undergone some minor modifications [13]. The scavenging coefficient takes the form

$$\Lambda = ar^b, \tag{2}$$

where $r$ is the precipitation rate in mm hr$^{-1}$ and $a$ and $b$ are parameters which can vary for different types of precipitation (rain / snow) or cloud phase (liquid / ice), for different scavenging processes (in-cloud / below-cloud) and for different species. Feng [4] showed that bulk parametrizations can significantly overestimate the scavenging of aerosol mass in heavy or long-duration medium rains since they do not take into account reductions in the bulk scavenging coefficient with time due to

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changes in the particle size distribution of the atmospheric aerosol.

An explicit calculation of wet scavenging processes would require detailed aerosol and cloud microphysics schemes, representing the formation and growth of cloud droplets and cloud ice crystals and the life cycle of aerosols including their emission or formation, growth, aggregation and chemical transformations. For example, below-cloud impaction scavenging can be explicitly calculated according to

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\int_0^\infty \frac{\pi}{6}\, d_p^3\, \rho_p\, \Lambda(d_p)\, n(d_p)\, \mathrm{d}d_p, \tag{3}$$

where $d_p$ is the aerosol diameter, $\rho_p$ is the aerosol density, $n(d_p)\,\mathrm{d}d_p$ is the number of particles with diameters in the size range $d_p$ to $d_p + \mathrm{d}d_p$ represented by the mass $M$ and $\Lambda(d_p)$ is the scavenging coefficient for aerosols with diameter $d_p$. $\Lambda(d_p)$ is obtained by integrating over the raindrop size distribution,

$$\Lambda(d_p) = \int_0^\infty \frac{\pi}{4}\, D_p^2\, V_t(D_p)\, E(D_p, d_p)\, N(D_p)\, \mathrm{d}D_p, \tag{4}$$

where $D_p$ is the diameter of the raindrop, $V_t(D_p)$ is the terminal velocity of the rain droplet with diameter $D_p$, $N(D_p)\,\mathrm{d}D_p$ is the number of raindrops per unit volume with diameters in the range $D_p$ to $D_p + \mathrm{d}D_p$ and $E(D_p, d_p)$ is the collision efficency between an aerosol with diameter $d_p$ and a raindrop with diameter $D_p$. Here we assume that $D_p \gg d_p$ and $V_t(D_p) \gg v_t(d_p)$, where $v_t(d_p)$ is the terminal velocity of the aerosol with diameter $d_p$. The collision efficiency is the efficiency with which the aerosol coalesces with the raindrop on collision and can be obtained by an empirical expression (see [10]). These calculations are very difficult (if not impossible) in an offline model which has access to limited cloud and precipitation information and which do not have such detailed aerosol and cloud microphysics schemes.

## 2 A particle size dependent wet deposition scheme for NAME

Despite limitations on the sophistication of wet deposition schemes in offline Lagrangian models, variations in the scavenging coefficient due to particle size can be included [4, 5, 7]. Feng [4, 5] presents aerosol size dependent scavenging coefficients for below-cloud scavenging by rain and snow. For rain, a 3-mode parametrization for particles in the nucleation, accumulation and coarse modes is presented (although the coarse mode is subdivided into two bins, since the scavenging coefficient changes rapidly for the particle size between 10 and 20 $\mu$m) [4]. The wet depletion of aerosol mass using this 3-mode scheme compares well with an explicit size-resolved calculation, whereas the traditional bulk parametrization is seen to overestimate the wet scavenging of aerosol mass by a heavy rain or a long-duration medium rain [4]. Feng's 3-mode scheme is available in the Lagrangian model MLDP0. Recent developments in the Lagrangian model FLEXPART have added a particle size dependency to the impaction removal scheme [7]. The particle size dependent wet deposition scheme introduced into NAME and described here includes below-cloud and in-cloud parametrizations and is based on the work of Feng [4, 5] (below-cloud) and uses information on the

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fraction of aerosols in-cloud which are embedded in the cloud droplets or cloud ice crystals taken from Stier et al. [12] and Croft et al. [2] (in-cloud).

## 2.1 Below-cloud scavenging

Below-cloud scavenging is efficient for small particles with diameters < 0.01 $\mu$m and large particles with diameters greater than a few micrometers. For particles with diameters between 0.01 $\mu$m and a few micrometres, the scavenging coefficient can be smaller by up to a few orders of magnitude (see Figure 2 in [4] (rain) and Figure 5 in [5] (snow)). Below-cloud scavenging coefficients for snow depend on the shape of the snow particles. Feng [5] considers two typical shapes, namely plane and column. For both shapes, snow scavenging is efficient for very fine (diameters < 0.01 $\mu$m) and large (diameters > 2.5 $\mu$m) aerosol particles. Planar crystals have a higher scavenging coefficient than columnar crystals for the submicron range of aerosols. Columnar crystals are, however, more efficient at scavenging aerosols with diameters between 2.5 and 10 $\mu$m. Snow scavenging coefficients obtained from different experiments are highly variable, even for the same aerosol size and precipitation rate. This variation can be partially attributed to the variety of types and shapes of snow particles. There are limited studies published on below-cloud scavenging by snow and for this reason many authors use a rain scavenging parametrization for snow. Sparmacher et al. [11] found that, for aerosols in the accumulation size range, measured below-cloud scavenging coefficients over a range of precipitation rates are about five times larger for scavenging by snow than for scavenging by rain.

To account for the differences of scavenging efficiency for aerosols with different diameters, Feng [4] uses bin-defined wet scavenging coefficients, $\Lambda_i$,

$$\Lambda_i = a_i r^{b_i},$$

where $\Lambda_i$ is the mean mass scavenging coefficient for bin $i$, $r$ is the precipitation rate in mm hr$^{-1}$ and $a_i$ and $b_i$ are the scavenging parameters for bin $i$. The scavenging coefficients are assumed to be independent of time $t$ and the total aerosol mass in bin $i$, $M_i$, is depleted according to the equation,

$$M_i = M_i(0) \exp\left(-\Lambda_i t\right),$$

where $M_i(0)$ is the total initial aerosol mass for bin $i$. Here we adopt a variation on this approach, taking a few key aerosol diameter values $(d_p)_i$ with appropriate scavenging parameters $(a_i, b_i)$ and interpolating between key diameter values. This ensures that the scavenging coefficients are continuous with particle diameter and removes any discontinuities in the scavenging coefficient at bin boundaries. The key aerosol diameter values chosen and the associated scavenging parameters are given in Table 1 and are taken from plots showing continuous curves of scavenging coefficients against particle size (Figure 2 in [4] for rain and Figure 5 in [5] for snow). For snow, we use scav-

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enging parameters obtained from scavenging coefficients of columnar ice crystals presented by Feng [5], although, as noted above, there is significant uncertainty in scavenging coefficients by frozen precipitation. Figure 1 shows the variation with particle size of the below-cloud scavenging parameters ($a$ and $b$) in rain and snow adopted in the NAME particle size dependent wet deposition scheme, together with, for comparison, the bulk scavenging parameters (which do not vary with particle size) used by default in NAME and the scavenging parameters used in particle size dependent below-cloud scavenging schemes in other models. Note that for a precipitation rate of 1 mm hr$^{-1}$, the $a$ scavenging parameter equates to the scavenging coefficient ($\Lambda$ in s$^{-1}$). The minimum in the below-cloud scavenging coefficient for particles in the accumulation mode can be clearly seen. The bulk scavenging coefficients are intended to represent a mean value over all particle sizes. The below-cloud $b$ bulk scavenging parameter used in NAME for snow has long since been known to be low in comparison to values used in other models and values found in the literature. (We note that a similar observation concerning the in-cloud $b$ bulk scavenging parameter used in NAME resulted in an increase of the recommended value for snow (see Webster and Thomson [13]).) The particle size dependent scheme incorporated into NAME agrees well with Feng's 3-mode parametrization, which is to be expected since Feng's scheme forms the basis of the NAME particle size dependent scheme.

| Mode | Diameter ($\mu$m) | Rain | | Snow | |
|---|---|---|---|---|---|
| | | $a_i$ (s$^{-1}$) | $b_i$ | $a_i$ (s$^{-1}$) | $b_i$ |
| Nucleation / Aitken | 0.03 | $6.2 \times 10^{-3}$ | 0.62 | $2 \times 10^{-2}$ | 0.9 |
| Accumulation | 0.2 | $1.06 \times 10^{-3}$ | 0.61 | $6 \times 10^{-3}$ | 0.95 |
| Coarse 1 | 6 | 0.92 | 0.79 | 1.7 | 0.76 |
| Coarse 2 | 14 | 1.81 | 0.81 | 7 | 0.83 |

Table 1: Below-cloud scavenging parameters in rain and snow for four key aerosol diameter sizes, obtained from continuous curves of scavenging coefficients against aerosol diameter in [4, 5].

For aerosol diameters between the chosen key values, linear interpolation in terms of $\ln a$ / $\ln b$ and $\ln d$ is used (see Figure 1). For particles with diameters less than 0.03 $\mu$m and greater than 14 $\mu$m, the particle size dependent scavenging parameters are kept constant. This seems appropriate for large particles (see Figure 2 in [4] and Figure 5 in [5]) but, for the smallest particles, the scavenging coefficient increases with decreasing aerosol diameter. These very small particles are expected, however, to contain a small proportion of the overall atmospheric aerosol mass since they grow rapidly, and hence are short lived. Furthermore, from Figure 2 of [4] and Figure 5 of [5] one cannot determine typical scavenging coefficients for aerosols with diameters below that shown.

The classification of precipitation into rain or snow in the NAME wet deposition scheme is based on temperature (rain: $T$ > 270 K, snow: $T \leq$ 270 K). It is on this basis that the 'rain' or 'snow'

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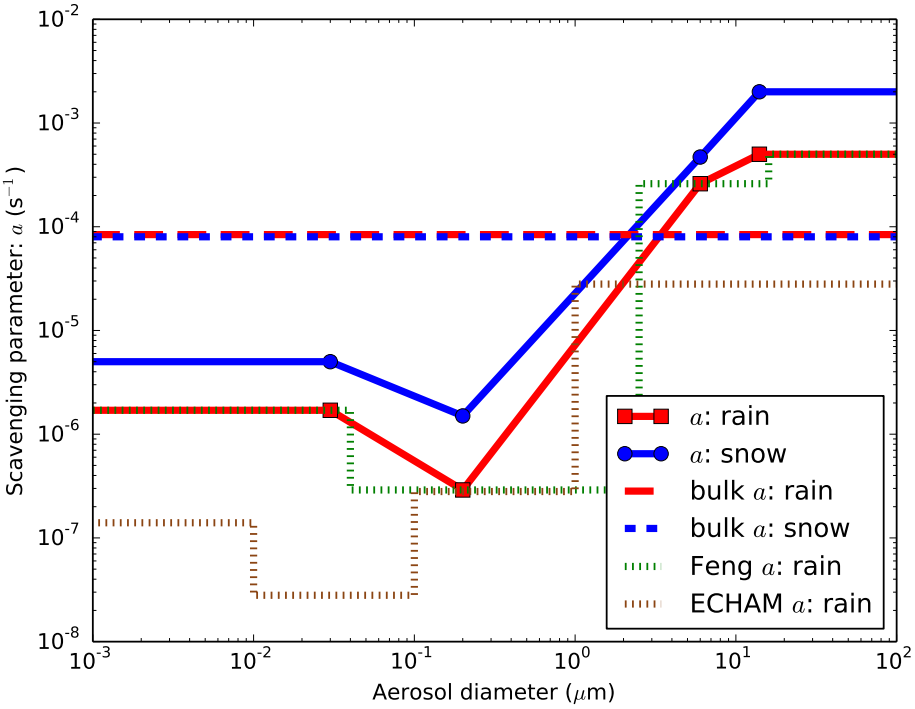
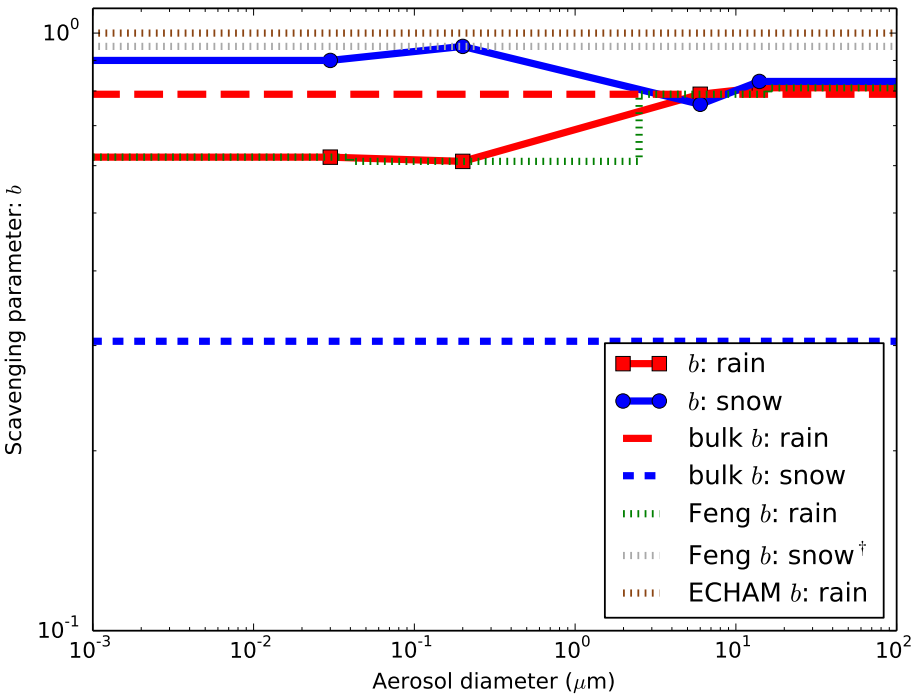



(a) scavenging parameter $a$




(b) scavenging parameter $b$

Figure 1: Variation of below-cloud scavenging parameters with particle diameter in the NAME particle size dependent wet deposition scheme. For comparison, the bulk scavenging parameters used by default in NAME and the particle size dependent scavenging parameters used in the MLDP0 [4, 5] and ECHAM [1] models are shown. (†personal communication)

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below-cloud parametrization is chosen using the atmospheric temperature at the particle's position.

## 2.2 In-cloud scavenging

In cloud, the particle size dependent wet deposition scheme in NAME uses different particle size bins ($i$) with a corresponding scavenging coefficient ($\Lambda_i$) which takes the form

$$\Lambda_i = a_i r^b = \widetilde{a} R_i r^b, \tag{5}$$

where $\widetilde{a}$ = 5.2 $\times$ $10^{-4}$ $s^{-1}$ and $b$ = 0.79 are constants which do not vary with aerosol size and $R_i$ is the in-cloud scavenging ratio for aerosol mode $i$. As advised by Feng (personal communication), we estimate $\widetilde{a}$ and $b$ from below-cloud scavenging parameters for rain (see Figure 2 in [4]) for particles with a similar size to an average cloud droplet (10 $\mu$m diameter). The in-cloud scavenging ratio is defined as the fraction of the in-cloud aerosol in mode $i$ that is embedded in the cloud liquid water / cloud ice and has the values given in Table 2, which are taken from Stier et al. [12]. $R_i$ depends on whether the aerosol is hygroscopic (soluble or water loving), e.g., volcanic ash, some particulate organic matter and some secondary organic aerosol, or whether the aerosol is hydrophobic (insoluble or water repelling), e.g., dust, black carbon, some particulate organic matter and some secondary organic aerosol. Values of $R_i$ for stratiform clouds given by Stier et al. [12] follow measurements of interstitial and in-cloud aerosol contents of Henning et al. [8], with slight modifications, and for ice clouds are based on Feichter et al. [3]. For mixed phase clouds, $R_i$ is lower than for liquid clouds due to the growth of ice crystals at the expense of water droplets as a result of the Bergeron-Findeisen process [8]. Nucleation of aerosols is not very efficient in ice clouds (i.e., most aerosols cannot act as ice nuclei). Stier et al. [12] also include in-cloud scavenging ratios for convective clouds. Assuming higher supersaturations and therefore activation into lower size-ranges, they increase $R_i$ in convective clouds for the soluble modes, assuming these modes to be potential cloud condensation nuclei. Relatively few size-resolved measurement data are, however, available for convective clouds. Furthermore, different scavenging rates in (by) convective and dynamic cloud (precipitation) are no longer used in NAME since high resolution convection resolving NWP models yield only total values of cloud and precipitation and do not distinguish between the different dynamic / large scale and convective forms. For these reasons, only the stratiform in-cloud scavenging ratios given in Table 2 are used in NAME. Although insoluble aerosols in the nucleation mode ($d_p$ < 0.01 $\mu$m) do not exist in reality, it is possible for the NAME user to specify such sized aerosols. Hence for any insoluble aerosols specified within NAME in the nucleation mode size range, the in-cloud scavenging ratios for soluble aerosols in the nucleation size mode are used. Note that, unlike the below-cloud parametrization, the in-cloud parametrization is discontinuous at particle bin boundaries. Without additional information on the variation of the scavenging ratio within aerosol bins, however, it is difficult to know how to construct an appropriate parametrization which varies continuously with particle size. The user should be aware, however, that results may be

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particularly sensitive to particle size at the bin boundaries.

| Aerosol / cloud type | Nucleation ($d_p \leq 0.01$ $\mu$m) | Aitken (0.01 < $d_p \leq 0.1$ $\mu$m) | Accumulation (0.1 < $d_p \leq 1.0$ $\mu$m) | Coarse ($d_p > 1.0$ $\mu$m) |
|---|---|---|---|---|
| **Soluble** | | | | |
| Liquid ($T$ > 0 °C) | 0.1 | 0.25 | 0.85 | 0.99 |
| Mixed (-35 < $T \leq$ 0 °C) | 0.1 | 0.4 | 0.75 | 0.75 |
| Ice ($T \leq$ -35 °C) | 0.1 | 0.1 | 0.1 | 0.1 |
| **Insoluble** | | | | |
| Liquid ($T$ > 0 °C) | | 0.2 | 0.4 | 0.4 |
| Mixed (-35 < $T \leq$ 0 °C) | | 0.1 | 0.4 | 0.4 |
| Ice ($T \leq$ -35 °C) | | 0.1 | 0.1 | 0.1 |

Table 2: The in-cloud scavenging ratios for different aerosol modes ($i = 1, \ldots, 4$) and different cloud types [12].

In NAME, temperature is used to determine the cloud phase (liquid: $T$ > 0 °C, mixed: -35 < $T \leq$ 0 °C and ice: $T \leq$ -35 °C). For the bulk parametrization, linear interpolation between the liquid and ice scavenging parameters is used in the mixed phase. Figure 2 shows the variation of the NAME particle size dependent in-cloud scavenging parameter $a$ with particle size in liquid, mixed and ice phase clouds for soluble and insoluble aerosols, together with, for comparison, the bulk in-cloud scavenging parameters (which do not vary with particle size) used by default in NAME. There is good agreement between the in-cloud $a$ scavenging parameters in ice clouds in the particle size dependent wet deposition scheme and the bulk scavenging scheme by frozen precipitation. The in-cloud scavenging parameter $a$ for insoluble aerosols is less than (or, at most, equal to) the corresponding value for soluble aerosols, whereas the bulk scavenging parameter does not vary with the aerosol solubility.

The chosen in-cloud scavenging parameter $b$ takes the value 0.79 (both in the particle size dependent scheme and the bulk scavenging parametrization). Feng (personaly communication) suggests values of $b$ = 0.8 for liquid phase clouds and $b$ = 0.96 for ice phase clouds.

# 3 Invoking the particle size dependent scheme in NAME

By default the bulk scavenging parametrization is used in NAME. The particle size dependent wet deposition scheme is invoked using the optional column keyword *Particle Size Wet Dep* in the *Species:* block. Allowed values are *Soluble*, *Insoluble*, *No* and leaving blank. The first two options invoke the particle size dependent wet deposition scheme for soluble and insoluble aerosols, respectively. (The user should recall that, in the particle size dependent wet deposition scheme, the in-cloud scavenging parametrization differs for soluble and insoluble aerosols.) The last two options invoke the default bulk scavenging parametrization. The particle size dependent wet deposition scheme is only available for sedimenting or non-sedimenting particle species. In other words, a

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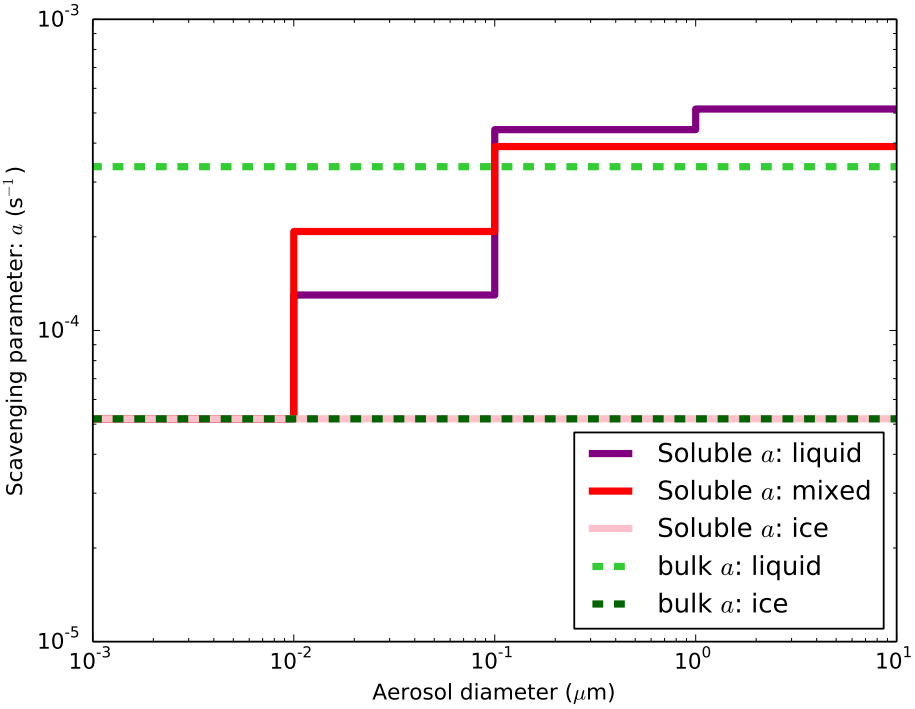
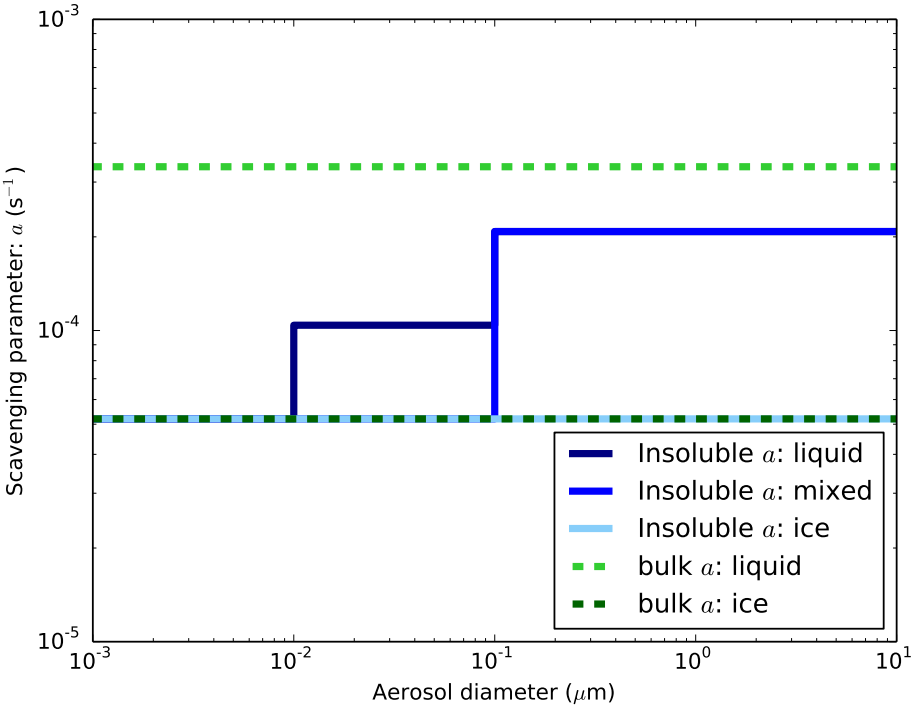



(a) Soluble aerosols




(b) Insoluble aerosols

Figure 2: Variation of in-cloud scavenging parameter $a$ with particle diameter in liquid, mixed and ice phase clouds for soluble and insoluble aerosols in the NAME particle size dependent wet deposition scheme. For comparison, the in-cloud bulk scavenging parameters used by default in NAME are shown.

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*Particle Density* and either a *Particle Diameter* or a *Particle Size Distribution* should be specified in the *Sources:* block (sedimenting) or a *Mean Aerosol Diameter* should be specified in the *Species:* block (non-sedimenting). The *Particle Diameter*, *Particle Size Distribution* or *Mean Aerosol Diameter* provide the aerosol diameter required by the particle size dependent wet deposition scheme. Note, however, that if a single diameter is specified (e.g., through a *Particle Diameter* or a *Mean Aerosol Diameter*) but intended to represent a range of particle sizes, then using the bulk scheme with $a$ and $b$ scavenging parameters chosen as appropriate average values may be better than using the size dependent scheme. This is because the scavenging coefficient at the mean particle size may not be a good estimate of the mean scavenging coefficient.

# 4 Testing

The particle size dependent wet deposition scheme has been used in a range of typical NAME runs modelling different particle species, and comparisons made with simulations using the bulk scavenging parametrization.

## 4.1 Ammonium sulphate

A simple continuous point release from ground level of a soluble atmospheric aerosol (ammonium sulphate, $(NH_4)_2SO_4$) with a typical atmospheric aerosol diameter of 0.4 $\mu$m was modelled and the total wet deposition fields obtained over the model run using both wet scavenging schemes were compared. Particles of this size are inefficiently scavenged by falling precipitation elements and hence the particle size dependent wet deposition scheme assumes smaller below-cloud scavenging coefficients than the bulk parametrization. In-cloud, the scavenging coefficients are similar in both wet deposition schemes for soluble aerosols of this size, with slightly higher scavenging coefficients adopted by the particle size dependent wet deposition scheme in liquid phase clouds than in the bulk parametrization. Figure 3 shows the time integrated wet deposition fields obtained using both wet scavenging schemes. The predicted fields are very similar, which is not unexpected since both fields are predicted by NAME using the same input meteorological data and, in particular, using the same cloud and precipitation information. There are, however, some subtle differences. Near to the release location, deposition amounts are slightly lower with the particle size dependent scheme, due to the smaller below-cloud scavenging coefficients. Since less aerosol is deposited near to source by the particle size dependent scheme, atmospheric concentrations are higher downwind and this can, in return, result in an increase in wet deposition amounts further afield.

## 4.2 Volcanic ash

The eruption of Eyjafjallajöull in 2010 was modelled using the particle size wet deposition scheme. Volcanic ash is assumed to be hygroscopic (soluble). The particle size distribution commonly used

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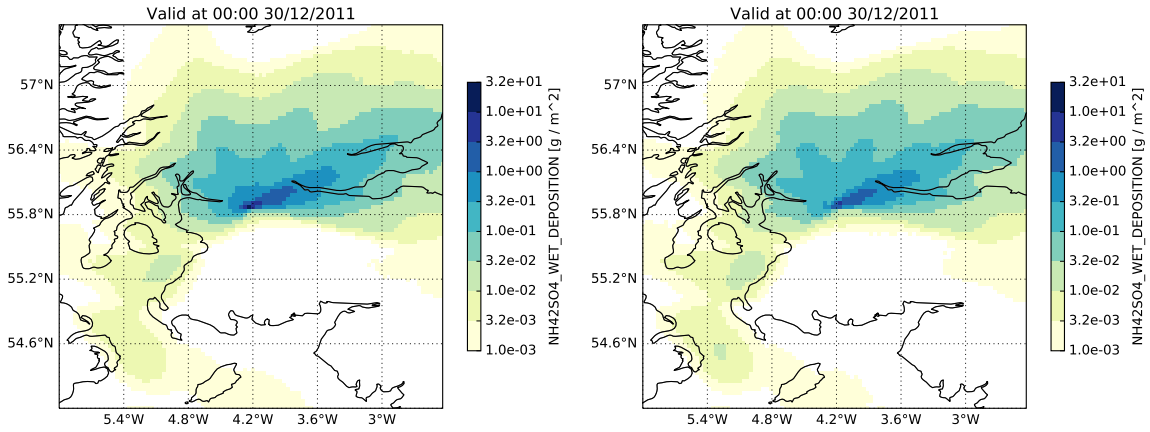


(a) Bulk scavenging coefficient

(b) Particle size dependent scheme

Figure 3: A comparison of time integrated NAME predicted wet deposition of $(NH_4)_2SO_4$ obtained using the bulk wet scavenging scheme and the particle size dependent wet deposition scheme.

for volcanic ash in NAME (see Table 3) represents ash particles up to 100 $\mu$m in diameter and is intended to only represent volcanic ash in the fine fraction which survives near source fallout. Within this size range, the majority of mass (70%) is placed in the coarse particle size range 10 - 30 $\mu$m. Figures 1 and 2a show that the particle size dependent wet deposition scheme for soluble aerosols adopts larger scavenging parameters than the bulk scavenging parametrization in this coarse size range. Consequently the particle size dependent wet deposition scheme deposits more volcanic ash, resulting, when there is significant wet deposition, in lower predicted air concentrations than when the bulk scavenging parametrization is used (see Figure 4). Comparing against observations of peak ash concentrations from the 2010 eruption of Eyjafjallajökull (as done by Webster et al. [14]), this slight reduction in predicted ash concentrations is again apparent with an increase in the number of under-predictions and a decrease in the number of over-predictions (see Table 4). The particle size dependent wet deposition scheme removes the tendency of the method of predicting peak ash concentrations described by Webster et al. [14] to over-predict airborne ash concentrations, giving a similar percentage of model over- and under-predictions. Furthermore, the particle size dependent wet deposition scheme has no detrimental effect on the run-time (in fact, in this test the run-time using the particle size wet deposition scheme was almost 2% less than the run-time using the bulk scavenging parametrization (see Table 5)).

## 4.3 Dust

Dust is hydrophobic and hence the NAME particle size dependent wet deposition scheme for insoluble aerosols is used here. The dust scheme in NAME determines a source term based on meteorological information (for example, near surface wind speed) and the underlying land surface. A particle size distribution is imposed for dust particle diameters ranging from 0.0632 $\mu$m to 63.2 $\mu$m (see Table 6). Mass is mainly released in the coarse size range with particle diameters

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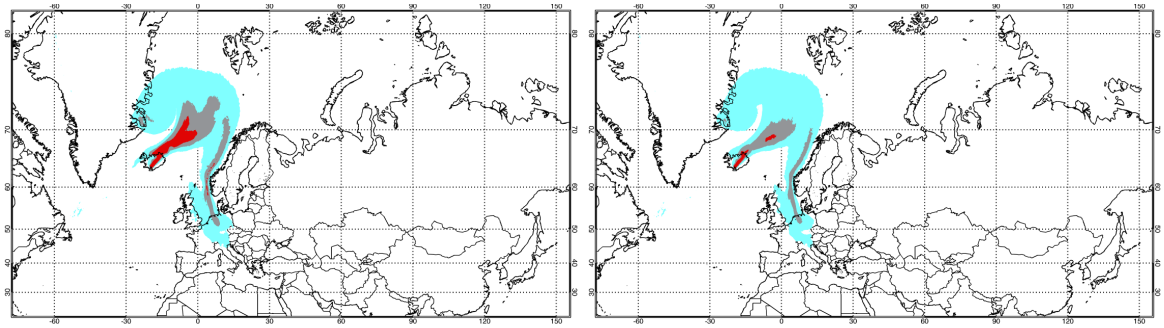
| Diameter range ($\mu$m) | Fraction |
|---|---|
| 0.1 - 0.3 | 0.001 |
| 0.3 - 1.0 | 0.005 |
| 1.0 - 3.0 | 0.05 |
| 3.0 - 10.0 | 0.2 |
| 10.0 - 30.0 | 0.7 |
| 30.0 - 100.0 | 0.044 |

Table 3: The default particle size distribution used in NAME for volcanic ash.



(a) Bulk scavenging coefficient

(b) Particle size dependent scheme

Figure 4: A comparison of NAME predicted 6-hourly averaged ash concentrations from the eruption of Eyjafjallajökull in 2010 using the bulk wet scavenging scheme and the particle size dependent wet deposition scheme. Peak ash concentrations between 12:00 - 18:00 UTC on 18/05/2012 and from FL000 - FL200 are shown in three concentration ranges: 200 - 2000 $\mu$g m$^{-3}$ (cyan), 2000 - 4000 $\mu$g m$^{-3}$ (grey) and > 4000 $\mu$g m$^{-3}$ (red).

| Wet deposition scheme | No model uncertainty | | | With model uncertainty | | |
|---|---|---|---|---|---|---|
| | % in agreement | % of over-predictions | % of under-predictions | % in agreement | % of over-predictions | % of under-predictions |
| Bulk scavenging | 24 | 44 | 32 | 55 | 27 | 18 |
| Particle size dependent | 27 | 38 | 36 | 56 | 21 | 23 |

Table 4: A statistical comparison of modelled and observed peak ash concentrations obtained using the hybrid max(25FL) peak ash concentration scheme (see Webster et al. [14] for details) and both wet deposition schemes. Agreement is assessed both with and without consideration of uncertainty in the model predictions due to positional errors in the ash cloud. Uncertainty in the observations is included in both assessments. (Note that the results presented here use a more recent version of NAME and hence results differ from those presented in Webster et al. [14].)

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| Wet deposition scheme | User time | Sys time |
|---|---|---|
| bulk scavenging | 38:11:50.25 | 00:13:41.47 |
| Particle size dependent | 37:27:46.02 | 00:12:45.70 |

Table 5: Run time comparisons between the bulk wet scavenging scheme and the particle size dependent wet deposition scheme for the simulation of the 2010 eruption of the Icelandic volcano, Eyjafjallajökull.

between 6.32 $\mu$m and 20 $\mu$m. For a precipitation rate of 1 mm hr$^{-1}$, Figure 1a shows that the below-cloud scavenging coefficients for particles in this coarse size range are larger in the particle size dependent wet deposition scheme than those used in the bulk scavenging scheme. For insoluble aerosols in this coarse size range, the in-cloud scavenging coefficients in the particle size dependent wet deposition scheme are slightly smaller for liquid and mixed phase clouds than those in the bulk scavenging scheme (see Figure 2b), but equivalent for ice clouds.

A 24 hour dust run for an arbitrary date in January 2008 is conducted using both the bulk wet scavenging parametrization and the particle size dependent wet deposition scheme. Figure 5 compares the NAME predicted total wet deposition over the 24-hour period obtained using the two wet deposition schemes. The particle size dependent wet deposition scheme deposits slightly more dust, which is not surprising since, as was seen for volcanic ash, below-cloud scavenging parameters are larger than the bulk scavenging parameters for coarse particles.

| Diameter range ($\mu$m) | Fraction |
|---|---|
| 0.0632 - 0.2 | 0.001 |
| 0.2 - 0.632 | 0.005 |
| 0.632 - 2.0 | 0.05 |
| 2.0 - 6.32 | 0.2 |
| 6.32 - 20.0 | 0.7 |
| 20.0 - 63.2 | 0.044 |

Table 6: The particle size distribution used in NAME by the dust scheme.

## 4.4 Radionuclides

The release of radioactive material following the accident at the Fukushima Dai-ichi nuclear power plant in March 2011 was modelled using NAME. Predicted deposition (both wet and dry) is compared against observations from an extensive sampling campaign carried out following the accident. ECMWF met data from the operational model at 0.125° resolution is used. The release of Iodine-

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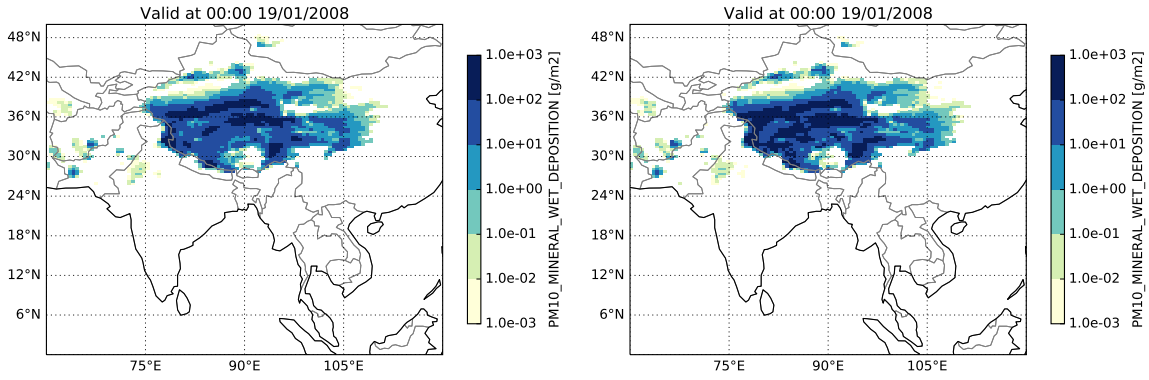


(a) Bulk scavenging coefficient

(b) Particle size dependent scheme

Figure 5: A comparison of NAME predicted 24-hour integrated wet deposition of dust obtained using the bulk wet scavenging parametrization and the particle size dependent wet deposition scheme.

131, in both gaseous and particulate form, and Caesium-137 is modelled. These radionuclides in particulate form are assumed to be hydroscopic and to have a particle size of 0.8 $\mu$m. Both airborne and deposited material undergoes radioactive decay.

Figure 6 shows the total deposition (both wet and dry) of Iodine-131 (in both gaseous and particulate form) predicted with NAME using the bulk wet deposition parametrization and the particle size dependent wet deposition scheme. The fractional bias obtained by comparing model predictions of deposited material to observations is also shown. The results obtained using the two different wet deposition schemes are very similar. Differences are, perhaps, less obvious, in this case, since dry deposition and the gaseous form of Iodine-131 are both included. For a particle with a diameter of 0.8 $\mu$m, the below-cloud scavenging coefficients for a precipitation rate of 1 mm hr$^{-1}$ are smaller in the particle size dependent wet deposition scheme than those used in the bulk parametrization (0.02 hr$^{-1}$ as opposed to 0.3 hr$^{-1}$ (rain), 0.06 hr$^{-1}$ as opposed to 0.29 hr$^{-1}$ (snow)). The in-cloud values are, however, similar.

# 5 Conclusions

A particle size dependent wet deposition scheme has been added into NAME. The scheme takes into account the known dependency of the scavenging coefficient on particle size and solubility. As such it enables changes over time in the bulk scavenging coefficient, due to changes in the atmospheric particle size distribution, to be represented. The effect on predicted wet deposition and air concentration fields for a range of aerosols has been assessed. Simulation runtime is an important consideration for models which are used in operational settings and the particle size dependent wet deposition scheme has no noticeable impact on the run-time of NAME.

Particle size information may not always be well known and hence, despite representing the

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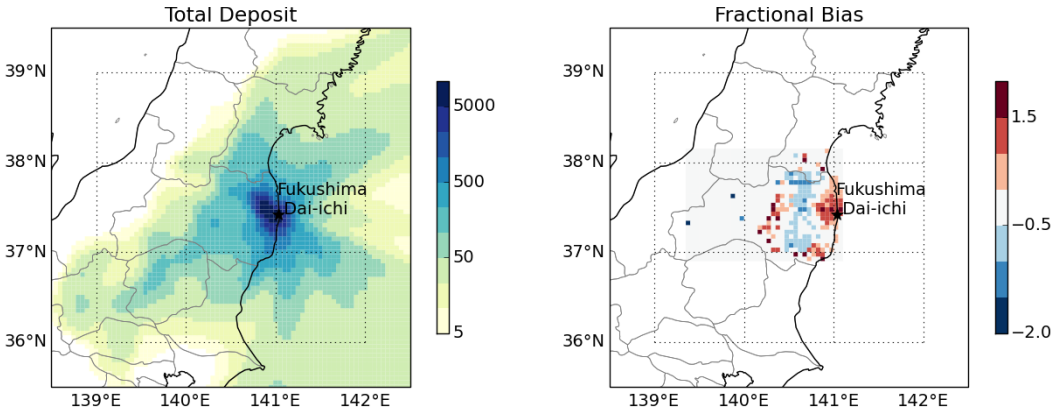
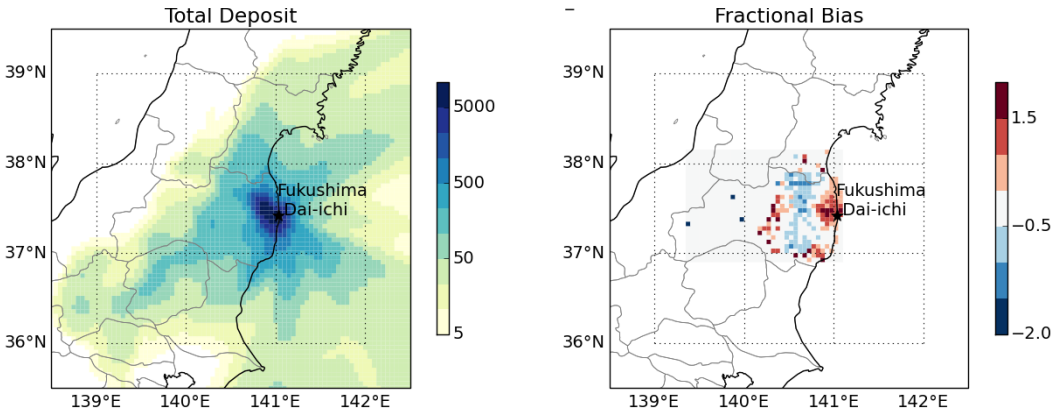



(a) Bulk scavenging coefficient




(b) Particle size dependent scheme

Figure 6: Total deposition (wet and dry) of Iodine-131 (gaseous and particulate) predicted using the bulk wet scavenging parametrization for particles and the particle size dependent wet deposition scheme, together with the fractional bias obtained from comparisons with observations.

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variation of the scavenging coefficient with particle size, uncertainties in the particle size distribution will translate into errors in the scavenging rate. Furthermore input cloud and precipitation data used by offline dispersion models is often crude and the accuracy of predicted wet deposition fields will largely be driven by the accuracy of this input data, regardless of the wet deposition scheme used.

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